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Analysis of Compression Techniques for Common Mapping Standard (CMS) Raster Data

By

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13. ABSTRACT *(Maximum 200 words)*
Current Common Mapping Standard (CMS) data, produced for the Mission Support System (MSSII) and other fielded systems, are in a spatially and color-reduced format, but are uncompressed. The next generation of CMS data must satisfy the functional, performance and quality requirements of a wide variety of systems from the mission planning, Theater Battle Management (TBM), intelligence and aircraft communities. Previous studies have indicated that a Vector Quantization(VQ)compression approach, combined with saptial downsampling and color reduction, can be implemented to achieve high quality compressed map products. The investigations described in this report use the previous studies as a base for this follow-on VQ compression analysis; further research has been performed in order to define a spatial reduction and VQ compression approach that can support both ground and airborne systems. The report recommends an approach to be used in the reduction and compression of the next generation CMS data that will satisfy the requirements of spatial density, displayed and printed image quality, image format and performance for CMS systems.

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The author acknowledges the work performed by David A. Southard (D047), which provided a basis for the compression analysis performed in this study. Section 2.1 summarizes the previous compression study and describes work performed more recently in the area of sharpening filters. Many thanks to Marie Francesca (D076), Mal Stiefel (D070), Paul Brown (D076), David A. Southard (D047), and Dan Scholten (D047) for their reviews and constructive comments.

EXECUTIVE SUMMARY

Common Mapping Standard (CMS) data will be used by a wide variety of systems, including full-scale and portable mission planning systems, aircraft cockpit display devices and Theater Battle Management (TBM) systems. Based on the geographic areas of interest for the systems and the disk storage requirements, a compression ratio of approximately 50:1 is required for CMS digital map and imagery data. The compressed CMS data format must provide adequate display and print quality to meet the requirements of all CMS-using systems. This study examined alternatives at each step in the downsampling and compression process, in order to define a compression scheme for inclusion in the second generation of CMS data. The goal of the study was to define a compression algorithm that produces data at approximately 50:1 compression and satisfies user requirements for spatial density, displayed and printed image quality, image format and performance. Major areas of research included the downsampling process and the Vector Quantization (VQ) compression parameters of codebook length, vector size and color table.

- *Downsampling.* The downsampling process decreases the number of pixels in an image and reduces the amount of disk space required to store the image. It is necessary to downsample the input ADRG charts in order to produce full-resolution displayed images of the appropriate size for mission planning and cockpit displays. Filtering of the input images is necessary during the downsampling step to eliminate digitization and downsampling artifacts. We examined several filtering methods and downsampling values to determine the optimum combination for CMS data.

- *Compression.* The VQ compression approach has been chosen for CMS data because it can be implemented with acceptable performance, because it provides a predictable compression ratio and because decompression is very fast. We isolated several steps of the compression process and examined quality and performance tradeoffs as compression parameters are modified.

The 55:1 compression scheme recommended in this report can be implemented on a wide variety of systems to produce high quality, interoperable, digital maps and images. Considerable savings in processing time, media costs and software development can be realized if this compression scheme is adopted for use in CMS data.

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INTRODUCTION

1.1 BACKGROUND

The Common Mapping Standard (CMS) data format will be used by a wide variety of systems, including full-scale and portable mission planning systems and aircraft cockpit displays. In general, mission planning users will receive data in a reduced and compressed format directly from a central data processing facility. In cockpit display systems, the Mapping, Charting, Geodesy and Imagery (MCG&I) data, along with specific mission information, will be transferred from the ground planning system onto a Data Transfer Device (DTD) for use in the cockpit. Because of stringent timing requirements for the transfer of data from the mission planning system to the DTD (six minutes for 100 megabytes in some cases [1]), it is necessary that no data transformation take place during the transfer of data between systems. Also, because both airborne and ground systems typically are required to utilize a larger geographic map coverage than on-line disks can store in an uncompressed format, compression of the data is required. This makes it necessary to define a compressed CMS data format that meets the requirements for all systems in terms of spatial density, image quality, and compression/decompression performance.

The Concept of Operations (CONOPS) of systems that will use CMS data varies over a wide range. While all users would opt for compressed data that is legible and has good color fidelity for both displayed images and hardcopy output, users' preferences for displayed image size and image file dimensions (which affect refresh rates), and the degree to which they can tradeoff performance, size, and compression ratio factors differ. The purpose of this research is to define a single format and compression scheme for the next generation of CMS data that will satisfy the requirements of these systems.

This report describes a series of experiments performed on various portions of the compression scheme in order to determine the best combination of factors to be used in the compression of CMS data. The report also describes the tradeoffs among compression schemes, spatial densities and data organization and recommends a combination of these factors for use in CMS data.

Throughout the report references are made to "first generation" and "second generation" CMS data. The current or "first generation" CMS data is documented in the CMS Interface Control Document (ICD) [2], which is currently under configuration control. These data are in a spatially and color-reduced format but are uncompressed. The analyses performed as part of this study will be used to recommend a compression format for the second generation of CMS data that will be documented in a military specification for raster/gridded products.

1.2 SCOPE

The requirements of ground mission planning systems in this document were obtained through Air Force Mission Support System (AFMSS) and Mission Support System (MSS II) documentation, and discussions with users of several Air Force and Army ground mission planning systems. Requirements for airborne cockpit display systems were obtained through discussions with several current and future users of airborne moving map systems as well as documentation from several aircraft cockpit display systems. The recommendations and opinions represented herein are based on our investigations and tests, and our current understanding of ground-based mission planning and moving map requirements.

1.3 ORGANIZATION

Section 2 of this report describes past investigations into VQ compression and the current requirements that drive the specific implementation recommended in this report. Section 3 describes analyses that were performed on several portions of the compression process. A summary of our findings, and recommendations for incorporating compressed data into a CMS format usable by ground systems and cockpit displays are contained in section 4.

SECTION 2

VECTOR QUANTIZATION COMPRESSION

2.1 PAST STUDIES

In response to the AFMSS program requirements for performance and storage space, MITRE performed a compression study in 1991 to determine an acceptable set of spatial reduction, image compression and color quantization parameters for ARC Digitized Raster Graphics [3] that met the requirements of the AFMSS Block B Specification [4]. The AFMSS Block B Specification calls for a spatial reduction of 4:1, a color reduction of 3:1, and a predictable, uniform compression ratio of at least 4:1, using a vector quantization (VQ) approach, yielding a total reduction/compression ratio of at least 48:1.

The investigation yielded a set of programs and recommendations that formed a minimum acceptable baseline for the AFMSS Block B requirements. It was recommended that the 4:1 downsampling be acco npanied by a cubic separable filter, defined in equation (1), which eliminates the digitization and downsampling artifacts and creates compressed output maps for graphic display with legible fine print. Details of the recommended cubic filter can be found in Mitchell and Netravali [5].

$$f(x) = \frac{1}{6}\begin{cases}(12-9B-6C)|x|^3 + (-18+12B+6C)|x|^2 + (6-2B) & \text{if } |x| < 1\\ (-B-6C)|x|^3 + (6B+30C)|x|^2 + (-12B-48C)|x| + (8B+24C) & \text{if } 1 \le |x| < 2\\ 0 & \text{otherwise}\end{cases} \tag{1}$$

In the above equation, x is the distance between pixels, normalized with respect to the resampled pixel width, and B and C are parameters that define the particular type of cubic filter. Recommended values are $(B,C) = (1/3, 1/3)$.

Another major finding in the 1991 study was that the best results are achieved when the red, green and blue color components are included in the VQ, with a color quantization of the codebook taking place after the VQ. Both uniform lattice color quantization (which uses n equally spaced values in the red, green and blue color planes) and custom color tables (which uses the "closest" n colors based on the input image) could be employed using the algorithms, with the custom colors giving superior quality. Section 3.3 in this report describes uniform lattice and custom color table generation and their incorporation into the VQ compression scheme.

Essentially, VQ compression, involves replacing each nxn vector in an input image with an index into an array or "codebook" of vector entries. The VQ approach, employed in Southard's study used a vector size of 2 x 2 pixels and a codebook length of 256, which resulted in the AFMSS-required 4:1 compression (or 48:1 total compression including spatial reduction and color quantization). The study also examined other vector lengths and codebook sizes and found that higher compression ratios often worked as well as the combined 48:1 required for AFMSS. It was found that a larger codebook and vector allows the clustering algorithm more degrees of freedom for tuning the codebook.

In response to users' concerns about the displayed and printed quality of AFMSS-generated products, a study was undertaken to determine if enhancement of the images after the downsampling step would lead to better quality output images. Experiments have indicated that photographs or visual signals with accentuated or crispened edges are often more subjectively pleasing than the original images [6]. An edge-sharpening filter called the *unsharp masking* filter was found to increase the sharpness of the lettering and contour lines in the digitized map images. In the unsharp masking process, a low-pass filtered version of the image is generated. A weighted difference between the normal and low-pass filtered images is then generated using the equation below. The sharpened image $F_S(i, j)$ is specified by:

$$F_S(i, j) = c(F(i, j) - F_L(i, j)) \qquad (2)$$

where $F(i, j)$ is the resampled chart image and $F_L(i, j)$ is a low-pass filtered version of the same image. For color images or maps this process can be performed separately for each R, G, and B color plane [6].

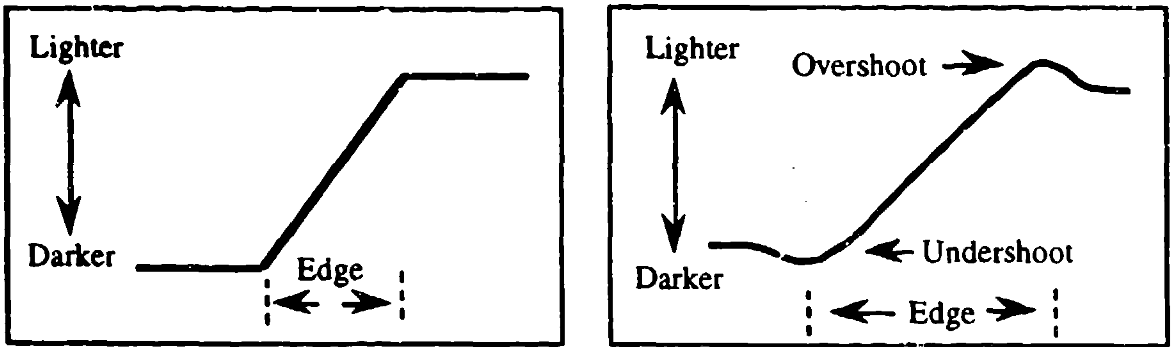
The masked image tends to have a larger gradient as well as an overshoot and undershoot as compared to the original image. Effectively, the dark side of an edge will appear somewhat darker and the light side of the edge will appear somewhat lighter, thus emphasizing the edge. The effect of the filter is shown in figure 1, which shows relative pixel brightness values over an image edge for non-filtered and unsharp mask filtered images, with the dark side of the edge on the left side of the figures and light side of the edge on the right side. The results of the unsharp masking filter along with the Mitchell cubic convolution filter applied to an image, are shown in figure 2.

2.2 CMS REQUIREMENTS

Currently, the AFMSS ground mission planning system is required to support the transfer of MCG&I data to DTDs for aircraft cockpit display systems. This new requirement necessitates a re-examination of the compression algorithms and the format of the CMS data, used by both ground and cockpit display systems.

2.2.1 Data Transfer Requirements

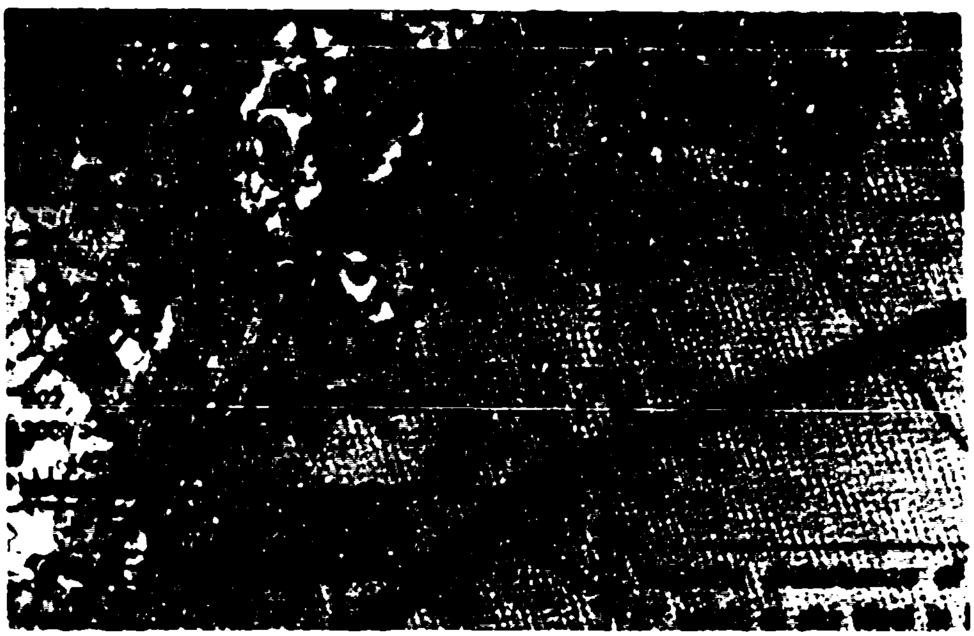
Many of the aircraft moving map systems, including those in the F-15, F-22, F-117 and MH-47K aircraft, will be receiving their data directly from the AFMSS Mission Planning



(a) Non-filtered Image

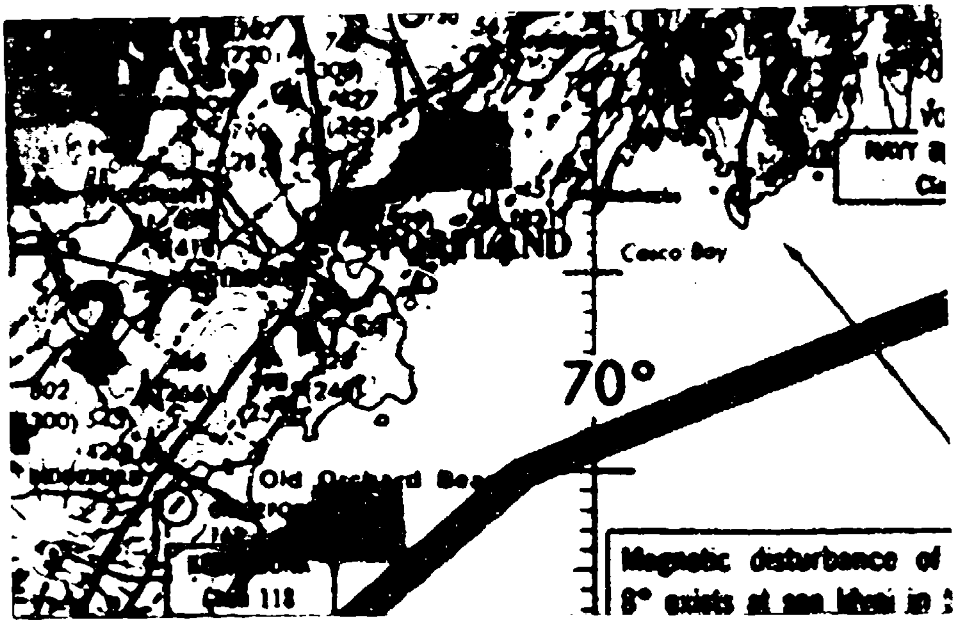
(b) Unsharp Masking Filter Applied

Figure 1. Typical Responses When Scanning Over an Object Edge [6].

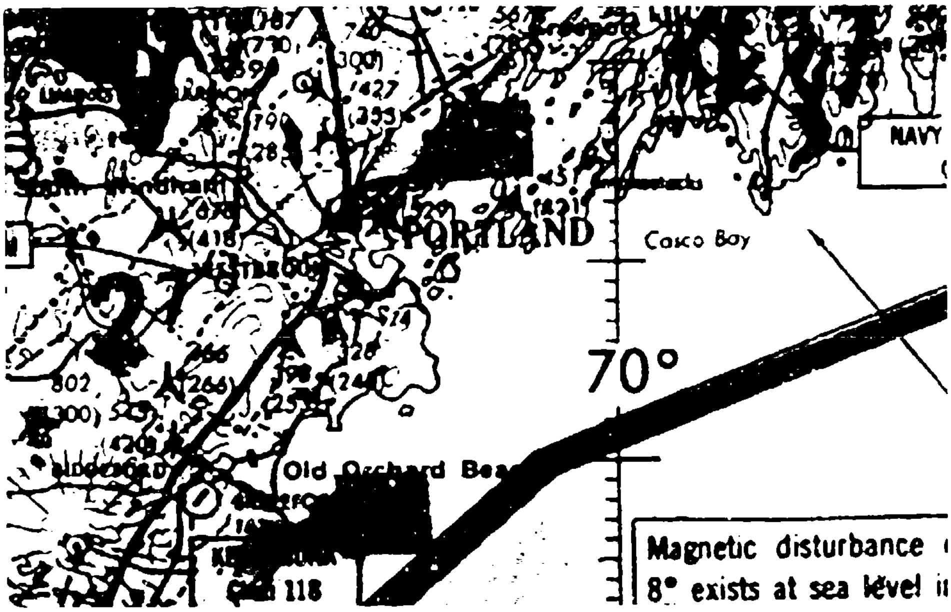


(a) Subsampled Image With No Filtering

Figure 2. Subsampled ADRG Data with Various Filters



(b) Subsampled Image With Cubic Filter and No Unsharp Masking Filter Applied



(c) Subsampled Image With Cubic Filter and Unsharp Masking Filter Applied

Figure 2. (Concluded)

Systems (MPS) [1,7]. The operational requirements for the mission planning process limit the amount of time to transfer the mission data, including MCG&I, to the data transfer devices. The time limit for some aircraft, including the F-15, has been set at six minutes for the transfer of 100 megabytes of data. This time limit requires a minimum of 463 Kbytes/second to be transferred to the data transfer device. The planned Small Computer System Interconnect (SCSI) cable connecting the MPS and DTD will be capable of handling this throughput. However, if transformations to the data (e.g., rescaling, reformatting) are required at the time of transfer, the six minute time limit will likely not be achieved. Rescaling and reformatting are CPU intensive tasks; depending on the transformations performed, the rescaling or reformatting of the data itself may require more than the allotted six minute transfer time. In this case, the transformation would need to be performed in the MPS before the time of data transfer to the DTD. It is therefore necessary to examine the requirements that drive data format, including pixel density, compression and frame/subframe sizes for both ground mission planners and moving map systems.

2.2.2 Data Format/Display Requirements

One major factor that will drive the format of the data is the refresh rate required in the cockpit display system. The concept of the "moving map" is that the display will show the current position of the aircraft superimposed on a map background. Some cockpit displays will provide the capability to scroll ahead to preview the terrain and obstacles further into the flight path. These capabilities require a rapid refresh rate, on the order of 20-30 screens per second, in order to provide smooth transitions from scene to scene [1].

The requirement for rapid refresh rates drives the need for constant size display elements. The current organization of CMS data in the ICD is inconsistent with this requirement. The first generation CMS framing structure is organized geographically. That is, each frame[1] or subframe for a product has the same latitude/longitude increments but differs in the number of pixels for each zone. Table 1 shows the frame and subframe sizes in pixels for two currently produced first generation CMS products. Subframe sizes, in pixels, are different for each CMS product in each zone. The number of pixels per frame and subframe can support the display requirements of the ground mission planners, but the large, variable subframe sizes make this organization inappropriate to support the rapid refresh rates required on moving map systems.

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1 A given frame is composed of a rectangular array of one or more subframes, each consisting of a rectangular array of pixels.

Table 1. Frame and Subframe Sizes in Pixels for First Generation CMS TPC and TLM Data

Zone	# Pixels/Frame (Longitudinal)		# Pixels/Subframe	
	TPC	TLM	TPC	TLM
1 and 10 (0° - 32° Lat.)	1028	2064	514	258
2 and 11 (32° - 48° Lat.)	844	1696	422	212
3 and 12 (48° - 56° Lat.)	684	1376	342	172
4 and 13 (56° - 64° Lat.)	556	1120	278	140
5 and 14 (64° - 68° Lat.)	456	912	228	114
6 and 15 (68° - 72° Lat.)	384	768	192	96
7 and 16 (72° - 76° Lat.)	308	624	154	78
8 and 17 (76° - 80° Lat.)	232	464	116	58
9 and 18 (80° - 90° Lat.)	------	------	------	------
Latitudinal	1114	2226	1114	2226

Typically, entire subframes are read into memory during display. More memory and time are used when large subframes that include many more pixels than are actually displayed on the screen are read in. When more than one subframe is to be displayed on the screen at once (i.e., a subframe border is crossed) still more time and memory are needed. For moving map systems, smaller, stable subframe sizes are required. We investigated the possibility of modifying the current geographic organization of the CMS data to a format based on constant subframe sizes of 256 x 256 pixels. This is considered a "natural" size because the blocking factor for most computers are powers of two, and image arithmetic operations can be performed more efficiently in some cases. This new format can support the needs of the moving map community, and will not have a negative impact on the ground planning systems. Section 3.4 discusses the options that we investigated in terms of numbers of subframes per frame, amount of overhead associated with each option and the effective compression ratio associated with all options.

Another area where agreement between moving map systems and ground-based systems is essential is the downsampling factor of the MCG&I data. Data transformations, including a rescaling of the pixels take a prohibitively long time, based on the timing requirements discussed in section 2.2.1. It is recommended that these transformations be done as part of the preprocessing of the data and that both ground systems and moving map systems use the same downsampling ratio as a base. Section 3.1 describes our investigations into downsampling the images to various pixel densities.

SECTION 3

ISOLATION STUDIES

The Concept of Operations (CONOPS) of many systems that will use CMS data varies over a wide range. For most systems, it is critical that all text and contour lines on the displayed and printed digital maps are readable and distinct. However, the preferences for spatial density, which determines the size of the full resolution displayed image, vary from program to program. It was our intent to find a single compression scheme that satisfies the requirements of all users in terms of compression ratio, display and print quality and displayed screen size.

Figure 3 shows a high-level process flow for the reduction and compression performed on the data, with each major step depicted. We undertook a series of experiments to analyze each step of the process flow individually. At each step, tradeoffs in quality and performance were examined, as well as the effect on the overall compression ratio. Sections 3.1 and 3.2 describe in detail each of the isolation studies.

3.1 DOWNSAMPLING

Downsampling is the process of uniformly reducing the spatial density of the pixels that make up an image. The downsampling process reduces the number of pixels in an image and decreases the resolution of the image (i.e., each pixel in the downsampled image represents a larger area). The quality of the downsampled image is greatly affected by the algorithms and filters used to perform the downsampling [6]. In these experiments, we used combinations of the cubic separable reconstruction filter and sharpening algorithms described in section 2.1 that were found to produce superior downsampled images.

3.1.1 Pixel Density

DMA digitizes the hardcopy maps used to make ADRG data at a sampling density of 100 microns or 254 dots per inch (DPI). Typical CRT displays have a density of 80-100 DPI, and therefore, raw ADRG data, as displayed on a CRT will appear to the user to be magnified approximately 2.5-3.0 times larger than the original map product in the x and y directions. The original requirements for the AFMSS system stated a downsampling factor of two in each direction (127 DPI), which created a slight magnification of the image, as compared to the hardcopy.

In the moving map community, the requirements for downsampling vary over a wide range. In moving map systems where the CONOPS requires that the fine print be legible by the pilot (e.g., F-15E), the sampling density is required to be fairly high (150-160 micron spacing, or 160-170 DPI). This increases the size of the map as displayed on the screen and creates a pixel pitch of the fine print on the map that is legible at the cockpit distance between the pilot and display screen. Some moving map systems, including the SOF Army Helicopters (MH-60K, MH-47E) use the cockpit maps as an overview only, and the legibility of the fine print is not a critical requirement. The preference for displayed map sizes in these cockpits is at or near actual map size. This requires a pixel density of approximately one-half the density required by moving map systems where legibility is a critical requirement. The Army is currently sponsoring an investigation to determine if CMS data at 169 DPI can be processed on the fly in the aircraft to meet their requirements.

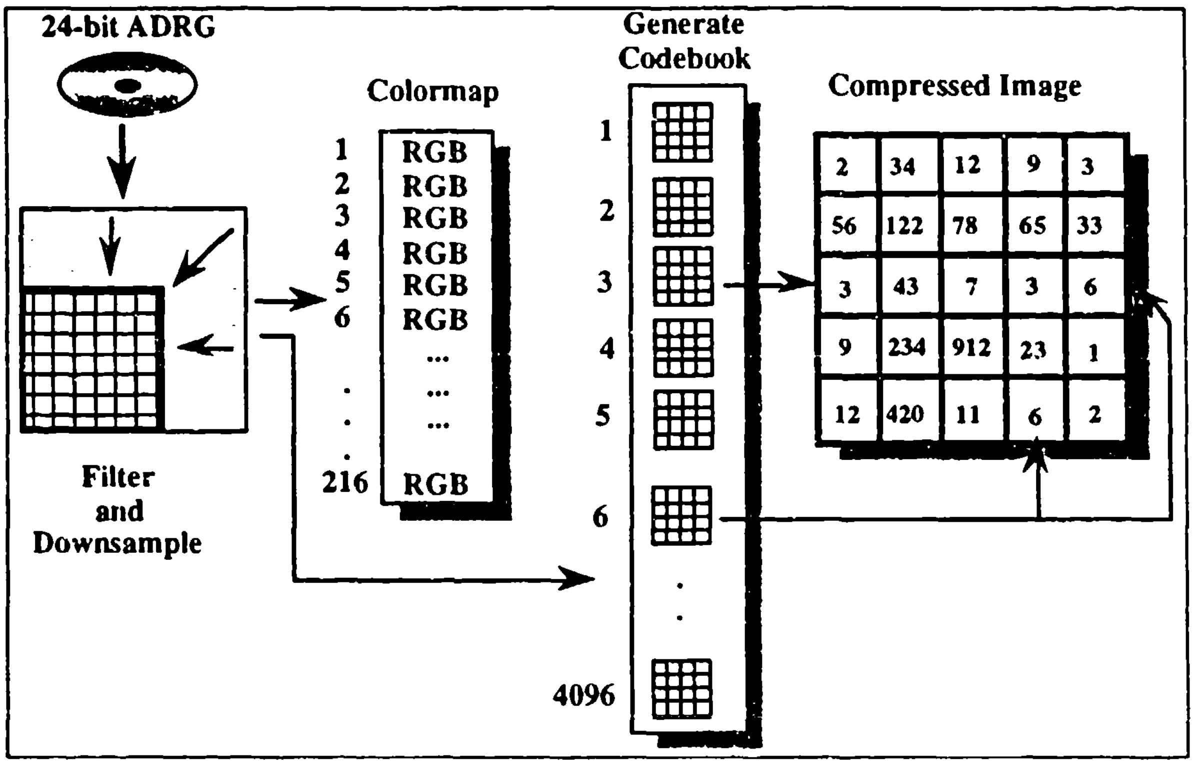
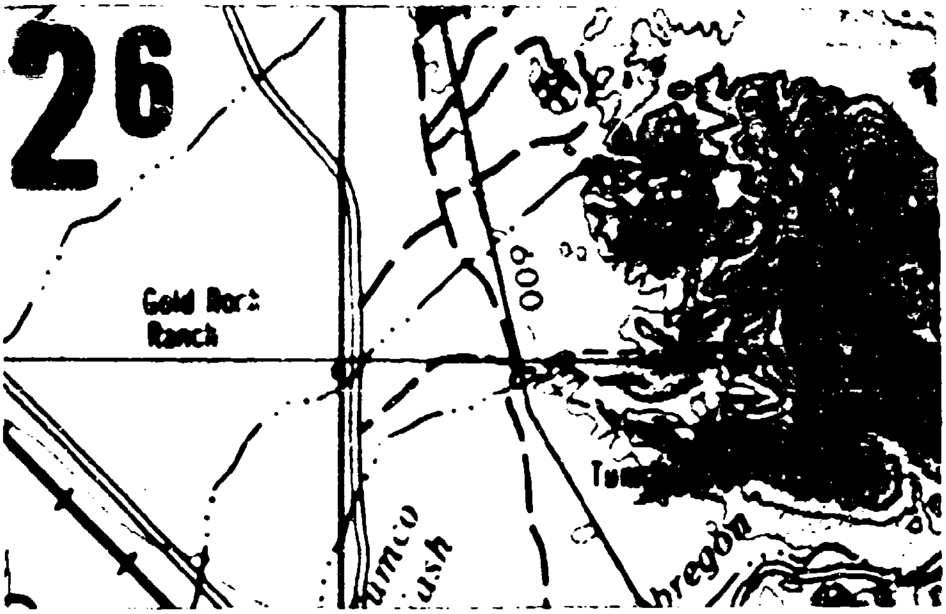


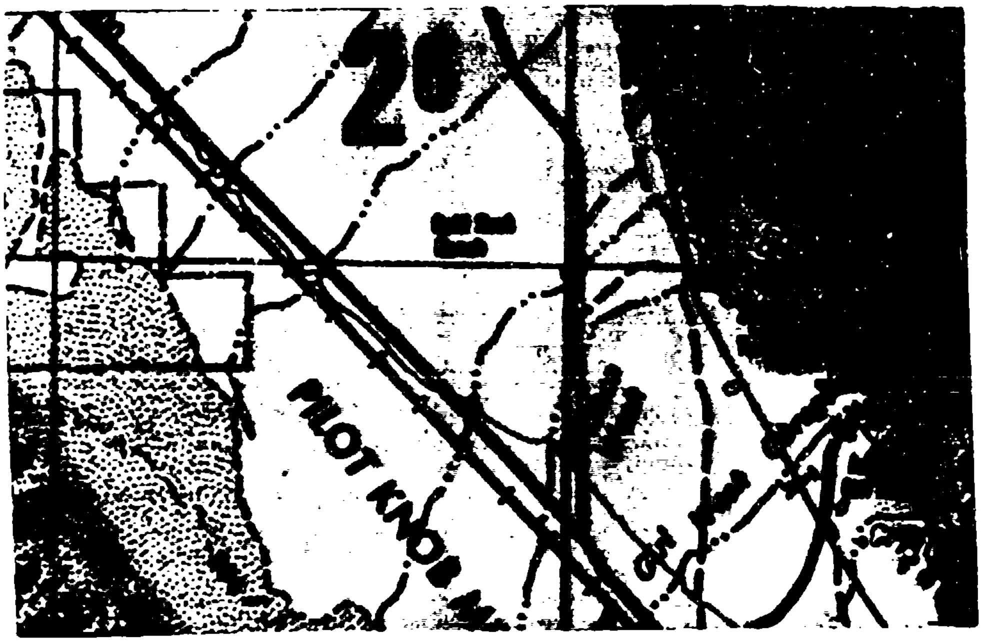
Figure 3. Process Flow for Downsampling and Compression

In this study, we investigated two downsampling densities; 127 DPI which is a slight magnification of the hardcopy maps, and 169 DPI (a noticeable magnification of the paper map size). Figure 4 shows a comparison of displayed map sizes, including raw ADRG, 127 DPI and 169 DPI after downsampling and sharpening, and before compression. All images are the same physical size but show different geographic extents.



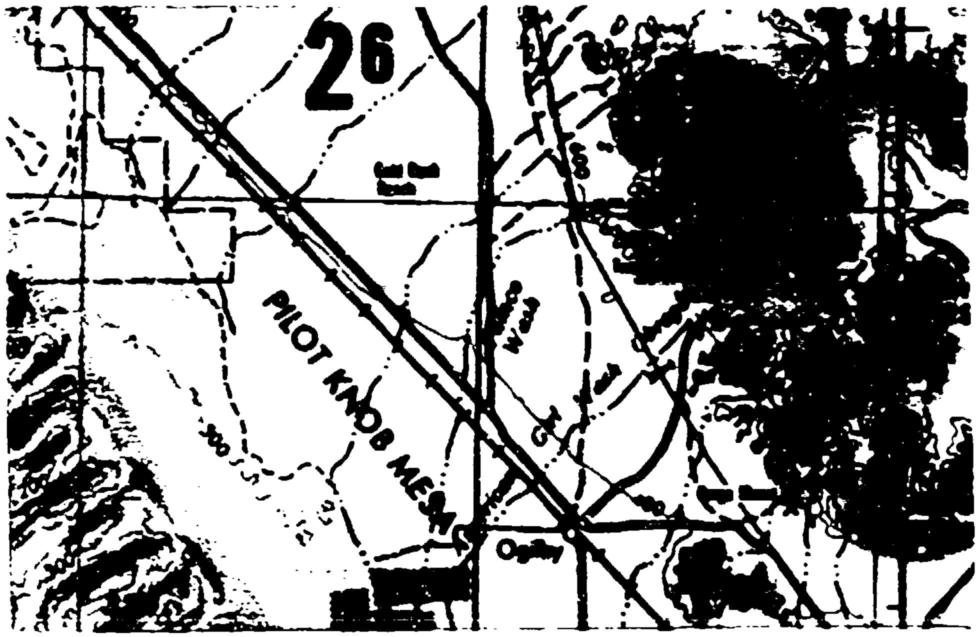
(a) Raw ADRG Data

Figure 4. ADRG JOG Charts Downsampled to Various Pixel Spacings



(b) JOG Chart Downsampled to 169 DPI

Figure 4. (Continued)



(c) JOG Chart Downsampled to 127 DPI

Figure 4. (Concluded)

The reduction in the amount of disk space required for storage of the reduced image is calculated as the square of the ratio between the pixel density before reduction to the pixel density after reduction. The reduction factor for the 127 DPI images is $(254/127)^2$ or 4:1. Similarly, the reduction factor for the 169 DPI images is $(254/169)^2$ or 2.25:1. This reduction factor is combined with the compression factors described in section 3.2 to determine the total image compression for a particular image. Figures 5a and 5b illustrate relative pixel spacing of images downsampled by 4:1 and 2.25:1 respectively. The 36 original pixels are replaced by 9 pixels in figure 5a and 16 pixels in figure 5b. It should be noted that the downsampled pixel locations will not necessarily fall on original pixel corners or edges.

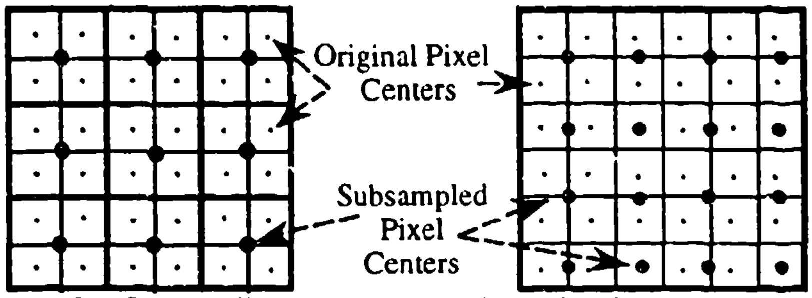


Figure 5a. Subsampling 4:1 Figure 5b. Subsampling 2.25:1

Figure 5. Relative Pixel Spacing for Downsampled Images

3.1.2 Downsampling Effects on Compression

The next step in the process is the compression of the downsampled images. The compression process is described in detail in section 3.2; a brief description of the interaction between downsampling and compression is given in this section.

Both the 127 DPI and 169 DPI downsampled images were combined with variable compression parameters including codebook length, and vector size (see section 3.2 for a description of the compression scheme). Our results indicate that the downsampling step in the reduction/compression process is one of the most critical in determining the quality of the final compressed image. We experimented with several combinations of downsampling and compression and found that degradation from downsampling could not be overcome by altering other steps in the compression process.

Some of the images downsampled at 127 DPI and subsequently compressed, exhibited downsampling artifacts that had a significant effect on their usefulness. We found that some contour lines disappeared, and fine print became illegible in places. The lettering within entire city areas became illegible when maps containing colored city areas were downsampled to 127 DPI and compressed to create an approximate 50:1 total compression.

3.1.3 User Feedback

Images downsampled from 254 DPI (100 μ pixel spacing) to 127 DPI (200 μ pixel spacing) and 169 DPI (150 μ pixel spacing) were shown to Air Force and Special Operations

Forces (SOF) users, as well as contractors and Navy personnel. Windows representing typical aircraft cockpit display sizes and full-scale ground planning display sizes were generated at both downsampling rates, in order to simulate the environment of a wide set of users. At a fixed display size, the 169 DPI (150 μ) images show approximately 30 percent less data in the x and y directions than the images downsampled to 127 DPI (200 μ). However, it was demonstrated that some of the fine print on the images sampled to 127 DPI and subsequently compressed could not be read by most people at a distance of approximately 2.5 feet due to one of two reasons. In the first case, the lettering was simply too small to read at that distance. In the second case, when users moved closer to the screen, the lettering became readable. In other cases, the lettering was illegible because of downsampling artifacts or because of the compression.

For ground mission planning purposes, the inability to read the fine print of a chart at a "normal" distance from the display screen can be compensated by zooming the image or leaning forward. In these cases, the legible fine print can be read. These options may not be available to pilots using moving map systems. The pilots cannot lean forward to a distance of 9-12 inches in front of the display screen, which was found to be necessary for some of the fine print in the images downsampled to 127 DPI. In addition, zooming of the displayed images may not be a capability of all moving map systems.

Hardcopy prints that were generated at the same scale using the 169 DPI and 127 DPI show similar results to the displayed images. There was some degradation in the printed products that were rotated to "track-up" orientation, but the 169 DPI, with a higher pixel density, produced better quality hardcopy prints.

3.1.4 Recommendation for Downsampling

It is necessary to determine one downsampling value to be used for the second generation of CMS data. As described in section 2.2.1, a rescaling of the data at the time of data transfer between the ground planning systems and the moving map systems would not meet requirements for total mission planning time. Our experiments show that the 169 DPI images are more legible on the display screen than the 127 DPI images. SOF Army aviation personnel require displayed cockpit maps to be at or near hardcopy map sizes. They are currently investigating the possibility of reducing the 169 DPI charts on the fly by a factor of two (to 85 DPI) in the cockpit such that their sizing and performance requirements can be met.

Another important issue in choosing the downsampling factor is the quality of the printed, compressed charts. It has been found that in many cases, printed copies of maps are of unacceptable quality when the displayed maps are marginally acceptable. This is due to the transformations required for printing including a rescaling to original hardcopy size, a reprojection to match the original hardcopy projection, and a rotation to create the flight-up strip charts needed by some flight crew members. It is therefore essential that the images available for printing are of the highest quality available, given the time and processing constraints. With other factors held constant, higher pixel density produces better hardcopy print quality. Another study is currently being conducted to investigate the effect of preprocessing (downsampling and compressing) and post-processing (rescaling, reprojecting and rotating) on hardcopy quality. Initial results indicate that hardcopy output quality fairly close to that of raw ADRG data can be achieved using a 169 DPI downsampling ratio and the compression parameters discussed in section 3.2.

After demonstrating sample images and discussing the issues with CMS users, we recommend using a downsampling value of 169 DPI (150 μ spacing, 2.25:1 reduction factor) for the next generation of CMS data. This downsampling rate produces displayed and printed maps of high quality at a size that is acceptable by most systems without zooming or reducing.

3.2 COMPRESSION

The VQ compression approach was recommended for AFMSS and will be employed in the next generation of CMS data for a number of reasons. First, VQ can be used to achieve a fixed compression ratio [8]. This allows system developers to accurately predict the amount of disk storage required for map data. Also, the VQ compression is fairly fast, compared to other image compression techniques. The decompression time associated with the VQ approach is very fast, requiring only a series of table lookups to decompress the image for display. The compression of digitized map data covering large geographic areas requires a significant amount of time. The parameters used in the VQ processing must be examined to determine optimum quality and performance trade-offs.

3.2.1 VQ Processing

Figure 3 showed a schematic of the downsampling and VQ approach. Essentially, the VQ approach involves segmenting the image into rectangular groupings of pixels called vectors. A list of vectors, called a codebook, is constructed through a clustering process, where entries in the codebook are determined that will minimize a distortion measure (usually squared error) for the compressed image. The codebook entries represent candidate values for the groupings of pixels within the image. Several clustering algorithms were examined by Southard [8] including the Linde-Buzo-Gray (LBG) algorithm [9] and the Pairwise Nearest Neighbor (PNN) algorithm [10]. In the report, it was shown that the PNN algorithm was faster than the LBG algorithm and had a higher quality in color images. We chose to use the PNN algorithm with a multi-dimensional (*k*-d) tree structure for clustering in our study.

In the PNN algorithm, the data (in our case *vectors*) are initially partitioned based on a single element of each vector (e.g., the first of the 16 pixels). After each partitioning, some of the vectors within each group are merged, based on local comparison of distortion. As the partitioning proceeds, different elements may be selected for partitioning each group (e.g., the second or third of the 16 pixels). One way of choosing the element to be used in partitioning would be to cycle through the pixels within the vector, first partitioning based on the values of pixel number 1, then partitioning based on the values of pixel number 2, and so on. Another way to partition the data is based on variance. Within each group the element with the largest variance can be used as the "split element". In this way, if the data are spread out along a particular dimension, then presumably differences in these coordinates are more "significant" in some sense than differences in another, more densely grouped element.

Figure 6 shows a flow diagram of the PNN algorithm, when using a k-d tree[10]. Essentially, the process is started by organizing a set of vectors into a k-d tree. After the tree is created, candidate pairs of vectors for merging are generated by doing local comparisons within each partition. A fixed fraction of these candidate pairs (such as 50 percent) are merged based on the distortion their merge would introduce. At this point, the process may stop if we have the correct number of clusters. If the process is continued, the k-d tree is repartitioned to account for the merging. The algorithm is described in detail in Equitz [10]. The code used to perform the clustering for the color table and codebook, and the subsequent compression and decompression is contained in Southard [8].

In the compressed image, each group of pixels is replaced by the index representing the codebook entry (from the clustering process) that most closely matches the particular group of pixels. For example, a group of pixels containing light gray pixels on one side and black pixels on the other side would be replaced by an index into the codebook; at the specified place within the codebook would be a grouping of pixels that had similar, but not necessarily exact values. Of the tens of thousands of pixel groups within an image, several groupings of pixels will have a similar distribution of values and therefore will be replaced by the same index into the codebook.

The basic VQ approach works with monochrome images, while the images that are used for mission planning and cockpit displays are typically color images. Southard [8] described an approach that included the pixels from the three color planes as part of the vector that is represented in the codebook. In this case, if the pixel block has a dimension of $n \times m$, the vector has a length of $3nm$. The color quantization is, in essence, performed at the same time as the image compression. By quantizing the codebook based on a 256-element color table before decompression, the image can be decompressed directly to 8-bit color table indices.

When an image is compressed, the n x m group of pixels for all color planes is replaced by a single index into the codebook. Because it takes fewer bits to represent the index into the codebook than to represent all the pixels in the group itself, the compressed image requires significantly less disk space. The theoretical compression ratio is determined by dividing the number of bits in each vector by the number of bits required to represent the

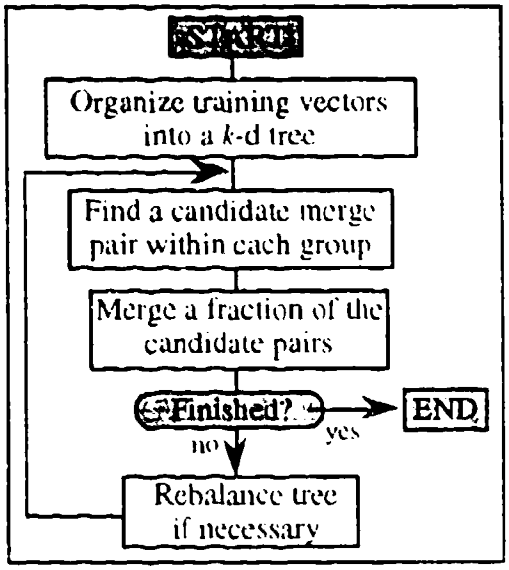


Figure 6. Flow Diagram for the PNN Clustering Process [10].

codebook index. In the paragraphs below we will be discussing the use of a 4 x 4 pixel vector and a codebook length of 4,096. The theoretical compression ratio for this scenario is 32, as calculated below:

$$f(x) = \frac{(Vector\_Length) \times (\text{\# bits per pixel in three color planes})}{\log_2 (M)} = \frac{16 \times 24}{12} = 32 \qquad (2)$$

where M is the number of vectors in the codebook and *Vector_Length* is given in bytes. Combined with a 2.25 spatial reduction, as described in section 3.1.1, the combined theoretical compression/reduction ratio is 72:1. The actual compression ratio depends on the size of the image that is compressed, and the overhead associated with the compressed image, including the storage required for the codebook, color table and any associated information that may be included in the header of each image. Equation 3 can be used to calculate the actual compression ratio for our compression scheme (derived from Southard [8]):

$$f(x) = \frac{(IW \times IH) \times (c)}{\frac{(IW \times IH)}{(Vector\_Length)} \times \frac{(\log_2 M)}{b} + (M \times Vector\_Length \times c)} = 24.7 \qquad (3)$$

In equation (3), IW and IH are the image width and image height respectively, b is the number of bits used to store each color component, and c is the number of color planes. This equation assumes that the entries in the codebook vectors are 8-bit indices to a color table. Combined with the spatial reduction and the CMS overhead, the compression ratio is 55:1. Decompression of the images involves a table lookup for each replaced group of pixels in the compressed image.

It should be noted that the compression ratios listed above assume that the 12-bits necessary to represent the 4,096 codebook vectors are stored in 1 and one-half bytes each. If bit-packing is not done, the theoretical compression ratio becomes 54:1 and the actual compression ratio is 44:1. Another study currently being conducted will determine the extent to which bit-packing increases the decompression time.

3.2.2 Vector Size Trade-offs

The AFMSS-specified reduction/compression scheme involved a 4:1 spatial reduction, and 12:1 combined color and image compression. As described in previous sections, the biggest degradation in quality was found to occur in the downsampling step. It is recommended that the amount of downsampling performed on the image be reduced from a total downsampling of 4:1 to a downsampling of 2.25:1. This increases the quality of the downsampled image, which in turn increases the quality of the compressed image.

In order to maintain the 50:1 or greater total reduction/compression ratio requ ed for ground planning stations and cockpit displays, the compression of the image must be increased to compensate for the lessened reduction. We experimented with increasing the size of the vector used in the compression as a way of achieving an adequate compression ratio with good quality. A 4-element vector had been used in previous compression studies described in this report. We investigated both a 9-element (3 x 3) and a 16-element (4 x 4) vector size in this study.

The theoretical compression ratios for the 3 x 3 and 4 x 4 vectors combined with the 2.25:1 reduction were 40.5:1 and 72:1, respectively. We found that both of these combinations produced compressed maps of high quality. However, the 3 x 3 vector size is not recommended for use with the next generation of CMS data because the effective compression ratio is too low. When the overhead of the color table and codebook is included, the effective compression ratio for the 3 x 3 scenario becomes 36.8:1. The comparable effective compression ratio for the 4 x 4 scenario is 55:1. The 16-element (4 x 4) vector size is recommended for use in the second generation compression scheme.

3.2.3 Codebook Size Trade-offs

With the increased number of pixels in the vector (and a corresponding increase in the pixel value permutations), we found it necessary to increase the number of entries in the codebook, in order to achieve an adequate level of image quality. Experiments were performed using codebooks with the number of entries ranging from 256 to 8,192; results of these experiments were shown to several Air Force, Army, and Navy users. Table 3 in section 3.3 shows the frame size, percent overhead and compression ratio for each scenario that we evaluated.

It was found that, with 1,024 or fewer entries in the codebook, the legibility of the decompressed map decreased and the contour lines began to break up and vary in width. Conversely, the legibility of the map produced with 8,192 entries in the codebook was very legible with no breakup in the elevation contours. There was very little quality difference between the map produced with 4,096 codebook entries and the map produced with 8,192 codebook entries.

Another factor considered was the amount of overhead associated with each codebook. Digital maps produced with a codebook length of 8,192 and a 4 x 4 vector size carry 128 kilobytes of overhead for the codebook itself (16 color table index values x 8,192 entries). This brings the amount of overhead to greater than 35 percent for digital maps in the size range that is being considered for CMS frames (see scenarios 4 and 5 in table 3). While having a large amount of overhead in itself would not necessarily rule out a particular compression scheme, the larger codebooks also cause performance degradation. Longer codebooks require more time to search than shorter codebooks.

The quality of the compressed image is affected by the clustering algorithm used to generate the codebook. Southard [8] used the Pairwise Nearest Neighbor (PNN) clustering algorithm with a *k*-d structure, defined in Equitz [10]. This algorithm was found to outperform the standard Linde-Buzo-Gray (LBG) [9] VQ algorithm in both speed and quality for color images. This structure can be used to perform a nearest neighbor search in $O(\log M)$ time [11], which makes it quite desirable for our purposes.

Based on our work and previous timing and quality analyses, we recommend using the PNN algorithm for the compression. In addition, we recommend a codebook length of 4,096, which we found produced a high image quality. The processing speed of the VQ compression scheme using the 16-element codebook vectors with 4,096 entries was found to be five to six times slower than using the 4-element codebook vectors with 256 entries. Longer search times account for the difference in performance. Another study currently being conducted is looking at faster search algorithms [12] for improving the performance of the compression algorithms. Alternative hardware options are also being investigated. Initial results indicate that modifications to the algorithms and hardware can significantly speed up the processing time such that performance timeliness for operational use of the data are adequate.

3.3 Color Tables

VQ compression does not restrict the type of color table that can be used for the images. The following paragraphs describe our examination of two types of color tables: a uniform lattice color table which, in our case, uses six equally spaced values in the red, green and blue color planes; and custom color tables that use the "closest" 216 RGB values based on the input image.

3.3.1 CMS First Generation Color Tables

The first generation of CMS data utilized a uniform lattice (6-6-6) quantization. In this scheme, the color information in the ADRG frame files is reduced from 24 bits/pixel in the source data to 8-bits per pixel in the frame file. Each frame contains one colormap with 216 colors composed of six discrete values each of red, green, and blue. For example, a given value of red in the table ($0 \leq \text{red} \leq 5$), represents a specific color in the 8-bit red portion of the DMA ADRG color spectrum, and similarly for the green and blue. Using the rounding method gives the index (0 through 5) into the red, green or blue color plane:

$$i_c = (C(m_c-1)+127)/255 \tag{4}$$

In the equation, C is the original (unquantized) value of the pixel ($0 \leq C \leq 255$), and m_c is the number of levels that we are quantizing (in this case, 6). The color table address (0 through 215) for a color can be defined as:

$$I = i_r + m_r(i_g + m_g i_b) \tag{5}$$

where i_r, i_g and i_b are the quantized RGB values for the pixel and m_r and m_g are the number of levels of quantization for the red and green planes. The corresponding color table entry contains the RGB values of $(255i_r/(m_r - 1), 255i_g / (m_g - 1), 255i_b/(m_b - 1))$. The total number of combinations of the values is (6 x 6 x 6) or 216, the number of colors in the color table.

As an example to illustrate the quantization of pixels using 6-6-6 lattice quantization, suppose an input pixel has RGB values of (39, 184, 79). Using equation 4 above for the 6-6-6 lattice quantization, the indices into the color table are (1, 4, 2). Table 2 shows the possible RGB values for pixels quantized to the 6-6-6 lattice; in our example, the color displayed on the screen would have RGB values of (51, 204, 102).

This standard color scheme can be used by systems that have only 8-bits of color available (such as current portable computers), without causing color shifts as different frames of data are displayed.

3.3.2 Color Table Recommendations

We experimented with both the 6-6-6 uniform lattice color tables and custom color tables. For the custom color tables, image sizes between 1,024 x 1,024 pixels and 2,304 x 2,304 pixels were used to develop the tables and the number of colors chosen for the table was 216. The PNN algorithm, previously described in section 3.2, was used for the development of the color tables.

As may be expected, the custom color tables offered better quality map images than the 6-6-6 uniform lattice color tables. Figures 7a and 7b show the differences between images compressed to 55:1 using custom color tables and 6-6-6 color tables. In general, the 6-6-6 color tables tended to be more gray, as the six color table values for the red, green and blue entries (e.g., 0,51 102, 153, 204, 255) are the same, as shown in table 2. Many of the RGB values in the map are quantized to the same color table entry in all three planes, and therefore are displayed as a shade of gray. As an example, an input pixel with RGB values of (60, 92, 75) would be quantized to (51, 51, 51). The 6-6-6 images also showed more mottling of colors (i.e., adjacent pixels that should map to a similar color are mapped to distinctly different colors). This is particularly noticeable in the background and in the lettering in the city area.

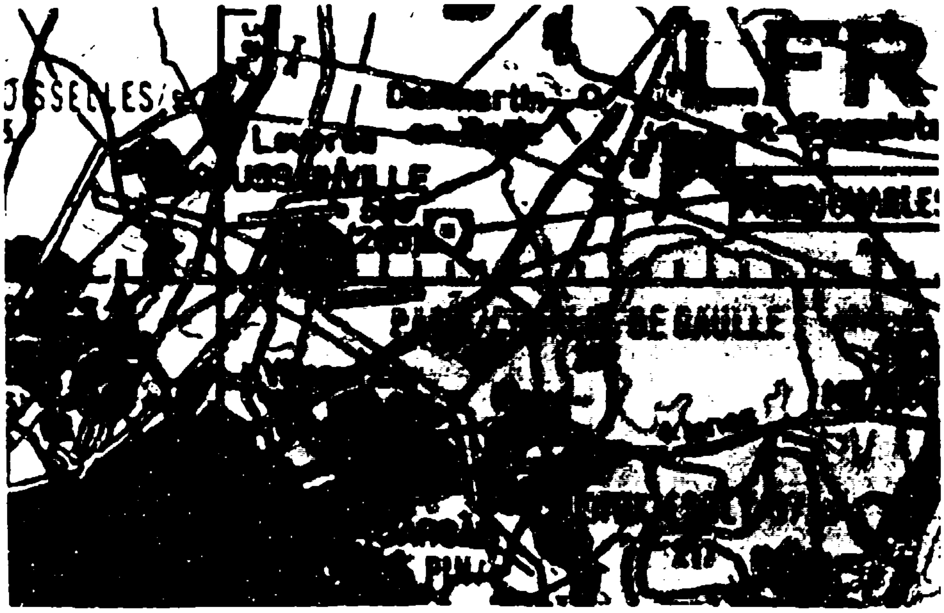
Table 2. RGB Values for Each Pixel in the 6-6-6 Uniform Lattice Color Scheme

Index	Red	Green	Blue
0	0	0	0
1	51	51	51
2	102	102	102
3	153	153	153
4	204	204	204
5	255	255	255

3.4 OVERHEAD

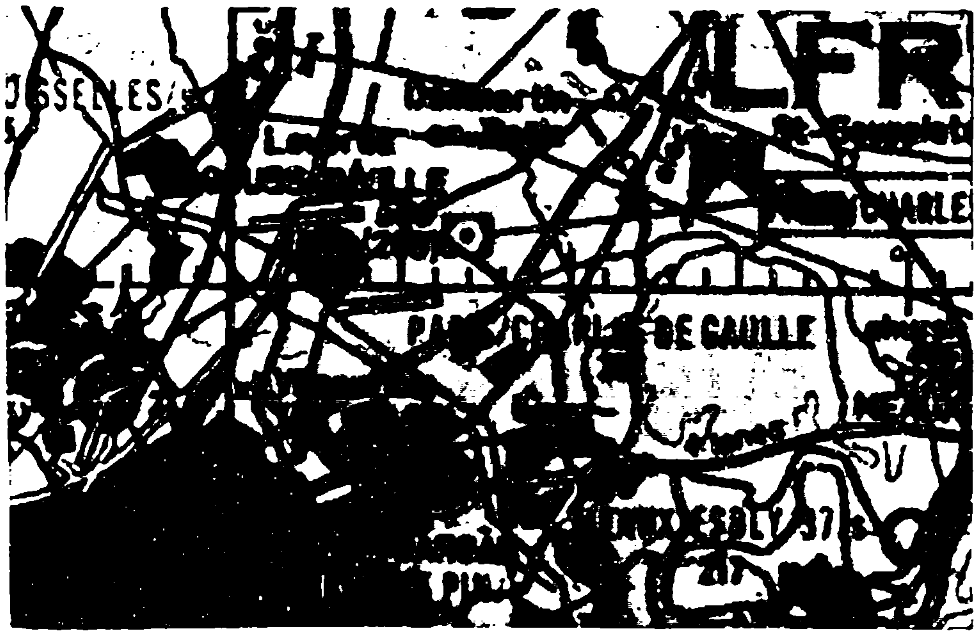
Several variables need to be taken into account before the recommendations concerning vector size, codebook length, and number of subframes per frame can be made. The total compression ratio is affected by all the parameters, with the size of the codebook having the greatest influence on the amount of overhead contained in the compressed image. Table 3 shows a comparison of several compression schemes with varying frame size, vector size, codebook length, and pixel spacing, and the effect of these parameters on the theoretical and actual compression ratio and the percent overhead. Several more possible combinations were examined and are discussed in previous sections of this report. Many scenarios were dismissed because of the poor compressed image quality, small total compression ratio, or poor performance of the compression scheme.

The recommendations made in section 4 reflect consideration of the quality issues discussed in previous sections of this report and overhead issues related to possible performance degradation.



(a) TPC chart, compressed 55:1 Using Custom Color Tables

Figure 7. Comparison of Charts Compressed Using Custom and 6-6-6 Color Tables



(b) TPC Chart Compressed 55:1 Using the 6-6-6 Color Table

Figure 7. (Concluded)

	Frame Size (Tiles Square)	Pixel Extents Of ADRG Image	Pixel Extent Of CMS Frame	Comp Vector Size (Pixels)	Code-book Entries	Reduced Pixel Spacing (microns)	Reduced Pixel Density (dpi)	CMS Image Size (Kbytes)	Codebook Size (bytes)	Total Overhead (bytes)	Total Frame File Size (Kbytes)	Overhead Percent Of CMS File	Theoretical Compression Ratio	Total Comp Ratio
1	5 x 5	1,984.0	1280	**4 x 4**	**4,096**	155.0	163.9	150	64	67	217	30.88	74.40	**53.14**
2	4 x 4	1,536.0	1024	**4 x 4**	**1,024**	150.0	169.3	80	16	19	99	19.19	86.40	**69.82**
3	6 x 6	2,304.0	1536	**4 x 4**	**1,024**	150.0	169.3	180	16	19	199	9.55	86.40	**78.15**
4	4 x 4	1,536.0	1024	**4 x 4**	**8,192**	150.0	169.3	104	128	131	235	55.74	66.46	**29.41**
5	6 x 6	2,304.0	1536	**4 x 4**	**8,192**	150.0	169.3	234	128	131	365	35.89	66.46	**42.61**
6	4 x 4	1,536.0	1024	**4 x 4**	**4,096**	150.0	169.3	96	64	67	163	41.10	72.00	**42.40**
7	6 x 6	2,304.0	1536	**4 x 4**	**4,096**	150.0	169.3	216	64	67	283	23.67	72.00	**54.95**
8	4 x 4	2,048.0	1024	**3 x 3**	**4,096**	200.0	127.0	171	36	39	210	18.60	72.00	**58.61**
9	6 x 6	3,072.0	1536	**3 x 3**	**4,096**	200.0	127.0	384	36	39	423	9.22	72.00	**65.36**
10	4 x 4	1,536.0	1024	**3 x 3**	**4,096**	150.0	169.3	171	36	39	210	18.60	40.50	**32.97**
11	6 x 6	2,304.0	1536	**3 x 3**	**4,096**	150.0	169.3	384	36	39	423	9.22	40.50	**36.77**
12	4 x 4	2,048.0	1024	**2 x 2**	**256**	200.0	127.0	256	1	4	260	1.54	48.00	**47.26**
13	6 x 6	3,072.0	1536	**2 x 2**	**256**	200.0	127.0	576	1	4	580	0.69	48.00	**47.67**

Table 3. Compression and Overhead Ratios Based on Various Compression Parameters

SECTION 4

CONCLUSION

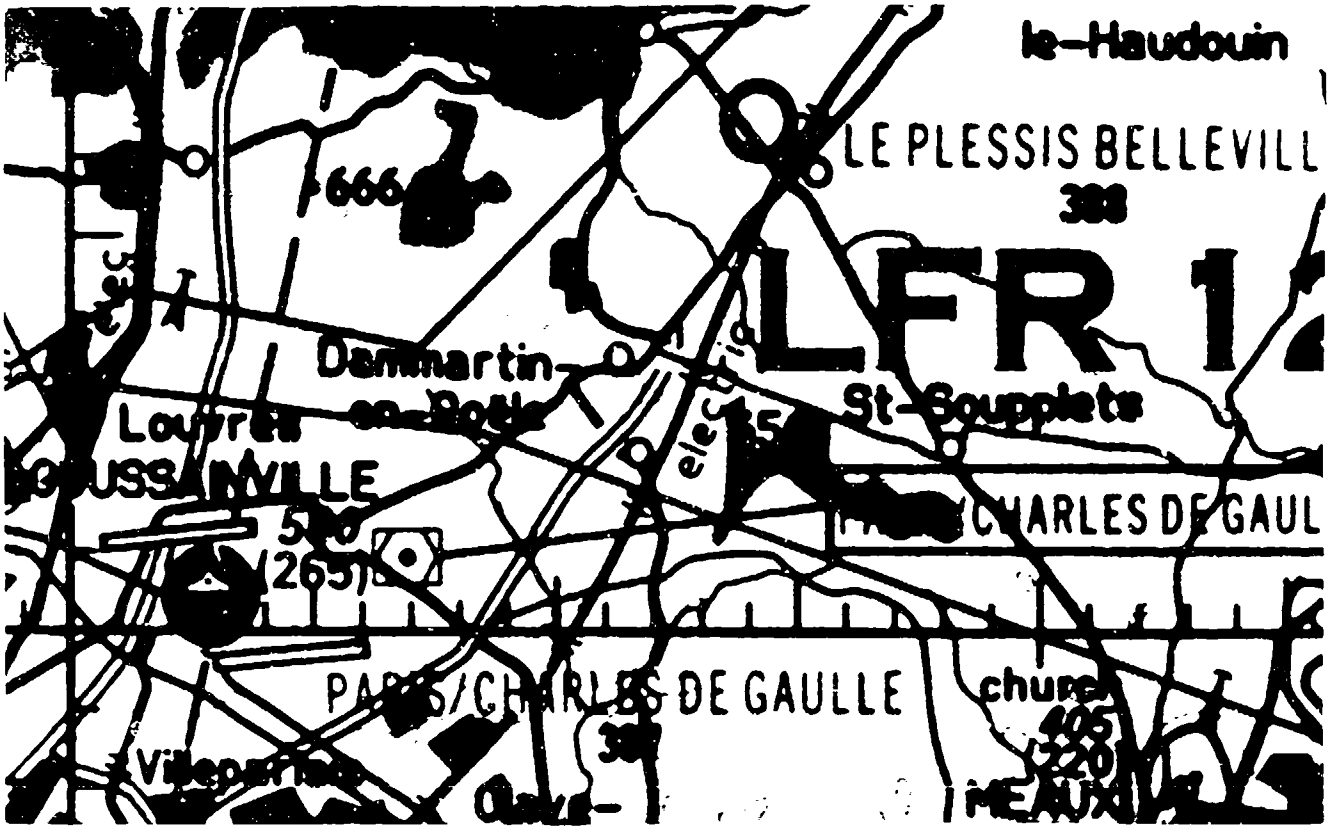
We were able to generate high quality images, compressed to a ratio of 55:1 from input ADRG charts. Figures 8, 9, and 10 show side-by-side views of portions of original ADRG charts and the corresponding 55:1 product. Little degradation can be seen in the 55:1 product. The most notable difference is the size of the images. Displayed raw ADRG data is approximately three times larger than the original map product, whereas the 55:1 product is closer to the size of the paper maps and more suitable for mission planning and moving map purposes.

4.1 RECOMMENDATIONS

We are recommending the 55:1 compressed data with the parameters described in previous sections for the second generation of CMS data. The option that we recommend is highlighted in table 3 and has an effective compression ratio (including overhead) of 55:1. The proposed compression scheme for the second generation CMS data was discussed and demonstrated at the 4 February 1993 CMS Interface Control Working Group (ICWG) meeting and comments from users and developers have been solicited. The specific downsampling, filtering, compression and frame size parameters that we are recommending for inclusion in the CMS raster/gridded military specification are summarized below:

- *Downsampling*. We recommend using a downsampling value of 169 DPI (150 micron spacing) for the next generation of CMS data. The total reduction from this downsampling is 2.25:1, which is less than the 4:1 downsampling currently used in the first generation CMS data. The change in downsampling rate is necessary in order to generate displayed and printed charts of the highest quality, given time and processing constraints, and the requirements for displayed print size in the aircraft. We recommend using the Mitchell cubic convolution filter during the downsampling step and the unsharp masking filter after the downsampling step. The two filters eliminate downsampling artifacts and generate crisp text and line features.

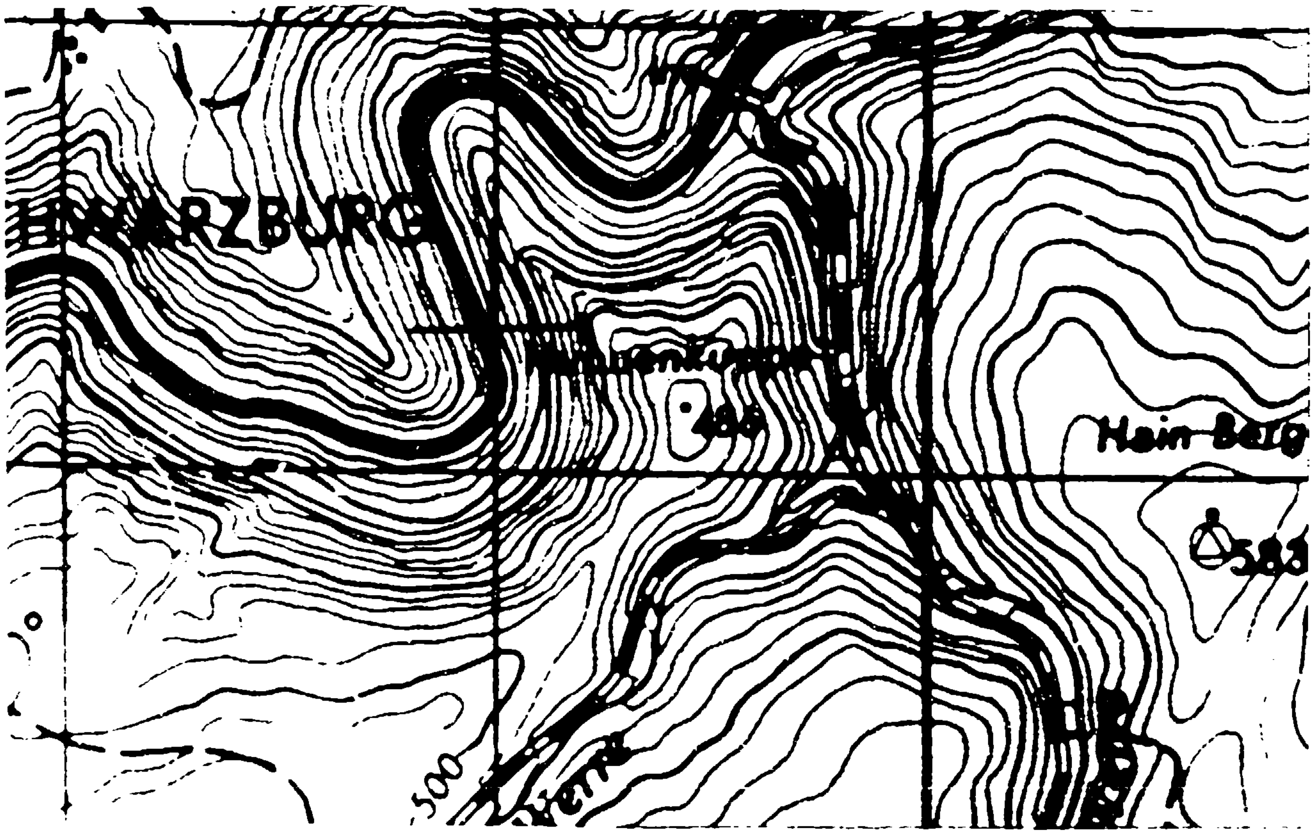
- *Frame/Subframe Size*. Based on projected performance values and display requirements which drive a need for constant sized display elements, we recommend a subframe size of 256 x 256 pixels. The number of subframes per frame is not restricted by the compression method we are proposing. In our studies, we used a downsampled frame size of 1,536, or 6 x 6 subframes, with one codebook per frame, and were able to achieve a high image quality. Because both performance and quality are affected by image size, we recommend using a frame size of 6 x 6 subframes or smaller for use with second generation CMS data (table 4).



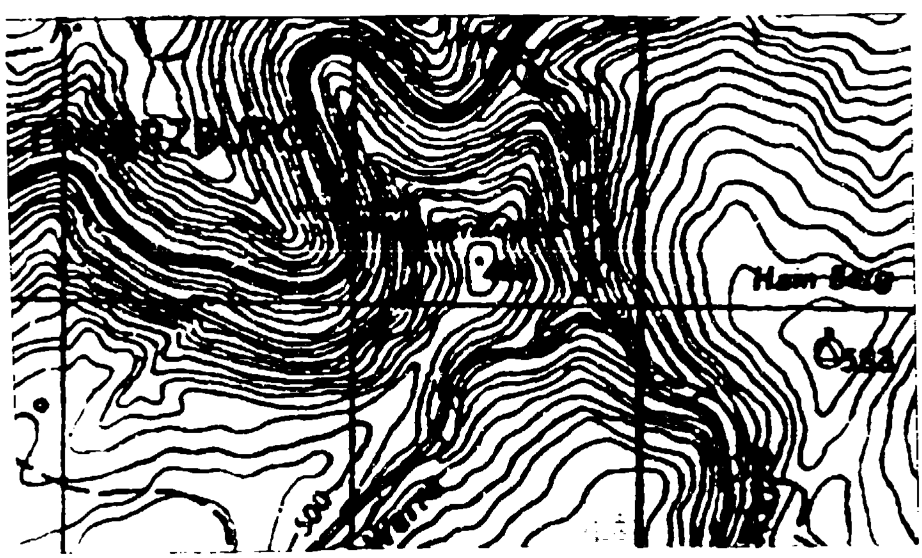
(a) Raw ADRG

(b) 55:1 Compressed Data

Figure 8. Raw ADRG and 55:1 Compressed 1:500,000 TPC Chart

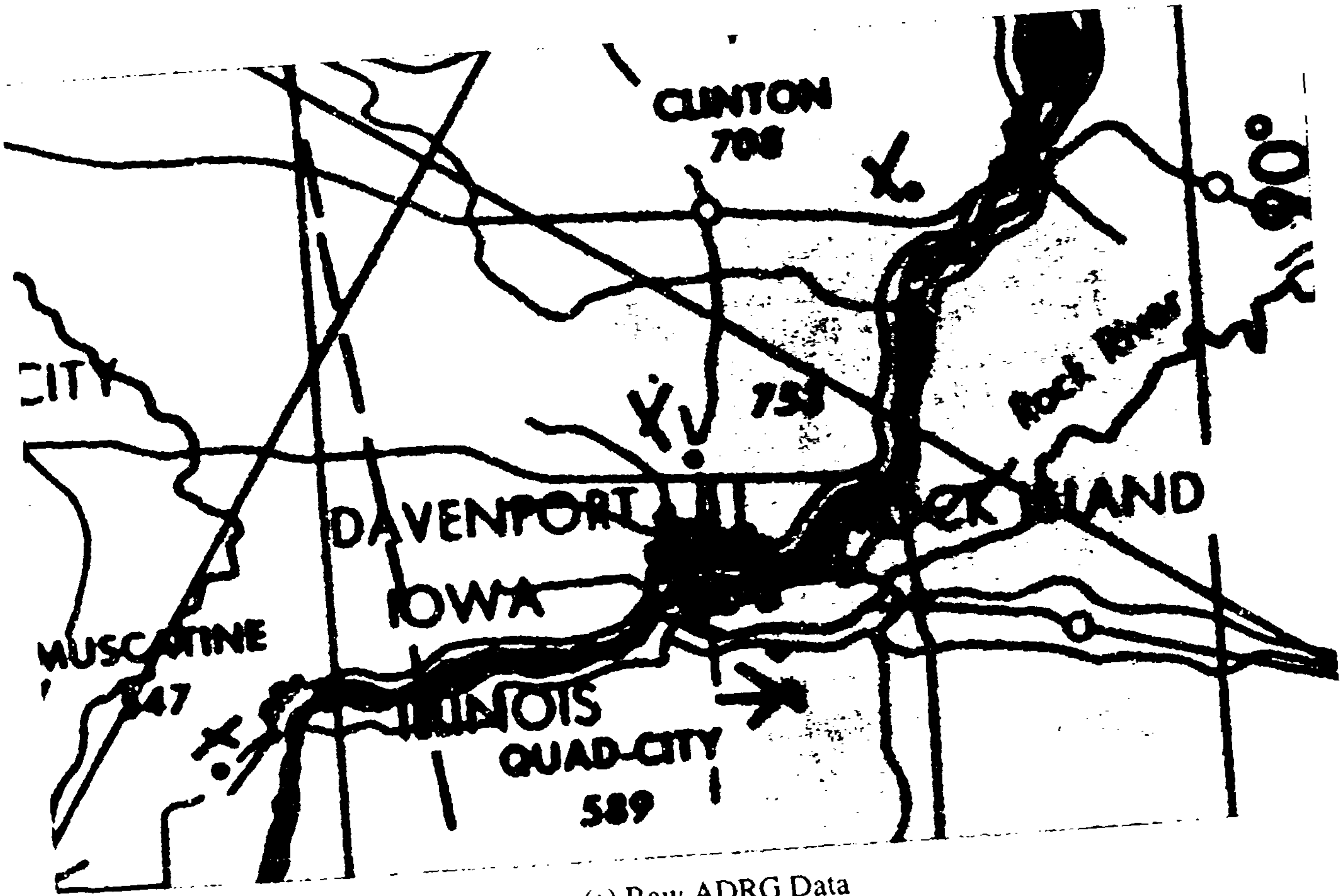


(a) Raw ADRG Data

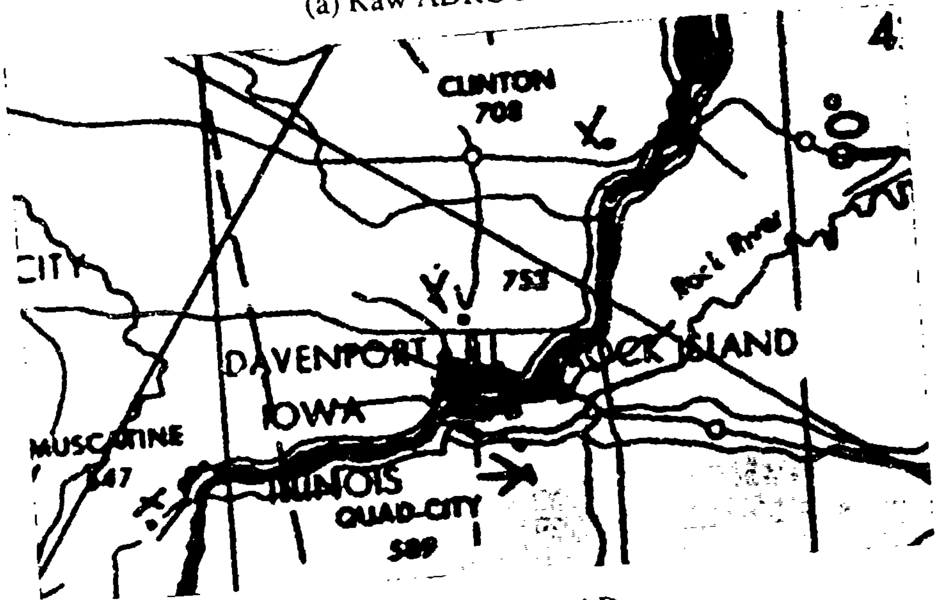


(b) 55:1 Compressed Data

Figure 9. Raw ADRG and 55:1 Compressed 1:50,000 TLM Chart



(a) Raw ADRG Data



(b) 55:1 Compressed Data

Figure 10. Raw ADRG and 55:1 Compressed 1:2,000,000 JNC Chart

Table 4. Proposed Frame Size for Second Generation CMS ADRG Products at All Scales

Zone	# Pixels/Frame (after downsampling)	# Pixels/Subframe
1 through 18	1,536	256
Latitudinal	1,536	256

- *Codebook Length/Vector Size.* In order to achieve the desired display and printed quality while maintaining a compression ratio of approximately 50:1, we found it necessary to decrease the amount of downsampling and increase the compression performed on the image. We experimented with vector sizes of 2 x 2, 3 x 3, and 4 x 4, and codebook lengths of 256 through 8,192. We found that a vector size of 4 x 4 combined with a codebook length of 4,096 produces high quality images, and we therefore recommend this combination of codebook length and vector size.

4.2 FUTURE WORK

There are several areas related to the implementation of the compression scheme that are currently being investigated. These studies are being conducted to provide improved performance in the compression algorithms, thereby increasing throughput at the CMS data production facility. In addition, the studies may provide specific recommendations for improving the exploitation of the CMS data. The studies are briefly described below:

- *Zone-wide Color Tables.* In this study we confined our color table work to uniform lattice (6-6-6) quantization and custom color tables, based on the values in one CMS frame (for our purposes, we used 1,536 x 1,536 pixels). To maintain high quality, and reduce the number of color tables that need to be accessed while displaying more than one frame of data or during panning operations, it is preferable to develop zone-wide color tables for each scale of map. In aircraft cockpit displays in particular, accessing more than one color table per display screen, or each time a frame boundary is crossed is not possible within the performance timeline of 20-30 screen displays per second.

  To develop zone-wide color tables, representative histograms for each scale in each zone are required. These histograms can be developed over time by incrementally modifying histograms for each scale and zone as maps are processed through the CMS data production facility. Representative histograms may already exist, as Compressed Aeronautical Charts (CAC) use zone-wide color tables, quantized to 240 levels (albeit, the zones in CAC data differ from the zones in ADRG charts). We will contact representatives at the Naval Research Laboratory (NRL), to determine if the histograms are available. We will also determine the feasibility of using the 240-entry color tables and re-quantizing them to 216 colors.

- *Performance*. The scripts and algorithms used to process the images have not been optimized for maximum performance. The processing speed of the VQ compression scheme using the 16-element codebook vectors with 4,096 entries was found to be five to six times slower than using the 4-element codebook vectors with 256 entries. A separate study is currently analyzing the code to determine if the clustering or compression algorithms can be modified for improved performance. In addition, the study is analyzing hardware options to determine an optimum hardware configuration for processing the data. Initial results indicate that processing and hardware improvements can reduce map processing time significantly.

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GLOSSARY

ADRG	ARC Digitized Raster Graphics
AFMSS	Air Force Mission Support System
ARC	Equal arc-second Raster Chart
CAC	Compressed Aeronautical Chart
CMS	Common Mapping Standard
CONOPS	Concept of Operations
CPU	Computer Processing Unit
CRT	Cathode Ray Tube
DMA	Defense Mapping Agency
DPI	Dots Per Inch
DTD	Data Transfer Device
GNC	Global Navigation Chart
ICD	Interface Control Document
ICN	Interface Change Notice
ICWG	Interface Control Working Group
JNC	Jet Navigation Chart
JOG	Joint Operation Graphic
LBG	Linde-Buzo-Gray
MCG&I	Mapping, Charting, Geodesy and Imagery
MPS	Mission Planning System
NRL	Naval Research Laboratory
ONC	Operational Navigation Chart
PNN	Pairwise Nearest Neighbor
RGB	Red, Green, Blue
SCSI	Small Computer Software Interface
SOF	Special Operations Forces
TBM	Theater Battle Management
TLM	Topographic Line Map
TPC	Tactical Pilotage Chart
VQ	Vector Quantization